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Future of the electric smart grid technology

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Abstract- Smart grid development tends to be driven by one of two principal visions for enhancing electric power interactions for both utilities and their customers In smart grids, users can influence utilities both indirectly by reacting to pricing signals and other mechanisms and directly by adding distributed generation sources, such as photovoltaic (PV) modules or energy storage at the point of use. This paper presents a discussion of the future of the electric energy system, addressing the entire spectrum from power generation, through substations, to distribution and the customer, and the feedback loops along the way necessary to provide the computational intelligence necessary to make the "Smart Grid". Both at the federal and state levels, governments have recognized a need for modernizing the electric energy system and establishing such Smart Grids around the world. We are at the point of a historic paradigm shift, with the opportunity to implement new, more intelligent methods for producing, distributing, delivering and using electricity in a much more sustainable manner. We discuss the necessary attributes for such a system-of-systems, review the need for change, and identify the technical challenges facing successful deployment and implementation.

Keyword:- Smart Grid, Adaptive Stochastic Control, Distributed Generation and Storage, WSN-Based Smart Grid Applications, Stationary and Mobile Energy Storage Systems

1.INTRODUCTION

Three dominant factors are impacting the future electric systems of the world; a government policy, efficiency needs of the consumer, and the introduction of new intelligent computer and hardware technologies. In addition, environmental concerns have created governmental policies around the world, including at the federal and state levels, which are driving the entire energy system to efficiency, conservation, and renewable sources of electricity. These factors are the main drivers that

are expanding the use of all sorts of new renewable energy and storage technologies on the one hand and new energy efficiency and conservation techniques on the other. Consumers are becoming more proactive and are being empowered to engage in the energy consumption decisions affecting their day-to-day lives. At the same time, they are expanding their energy needs. For example, consumer participation will ultimately include extensive use of electric vehicles (both cars and trucks), remote control of in-home appliances to promote energy conservation, ownership of distributed generation from ever more renewable energy sources, and management of electricity storage to locally match supply to demand. The availability of new technologies such as more abundant and aware SCADA sensors, secure 2-way communications, integrated data management, and intelligent, autonomous controllers has opened up opportunities that did not exist even a decade ago. The electric energy system of the future needs to address all these needs and concerns by using advanced technologies to create a smarter, more efficient and sustainable grid. During recent years, there have been numerous articles and conferences about the Smart Grid, but much confusion remains among all constituencies about just what the term entails. Although many different definitions have been proposed for the Smart Grid, in most cases the users have chosen particularly focused definitions related to their specific applications and local needs. Below, we define the Smart Grid in its broadest global terms. We begin with a description of the makeup of the present conventional electric energy system, and we then identify the areas that must change in order to provide the intelligence and control necessary to convert to the safe, secure, and efficient Smart Grid of the future.

2.THE CONVENTIONAL ELECTRIC ENERGY SYSTEM

A general description of today's conventional electric delivery system is represented in figure 1.

Traditionally the system is broken into mostly isolated components (silos): generation, transmission, substation, distribution, and the consumer. Key characteristics of this conventional system that will be most strongly impacted by the changes required to implement the Smart Grid are the following attributes:

1. Centralized sources of power generation,
2. Unidirectional flow of energy; from the source to the customers,
3. Passive participation by the customers; consumer knowledge of electrical energy usage is limited to a monthly bill received, after the fact, at the end of the month,
4. Real-time monitoring and control is mainly limited to generation and transmission, and only at some utilities, does it extend to the distribution system,
5. The system is not flexible so that it is difficult to either inject electricity from alternative sources at any point along the grid, or to efficiently and sustainably manage new services desired by the users of electricity.

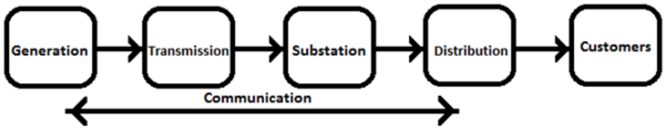

Figure1. Conventional Electric Grid

These conventional attributes have adequately served the needs of electric utilities and their customers in the past. However, the new needs of more energy knowledgeable, computer savvy, and environmentally conscious consumers, combined with regulatory changes that promote sustainability and energy independence from foreign sources, availability of more intelligent technologies, and ever greater demands for enough energy to drive the global economy, require an electric energy system of the future that is fundamentally different in all 5 areas listed above.

3.THE FUTURE SMART ELECTRIC ENERGY SYSTEM

A general schematic of the future electric energy system, or Smart Grid, is presented in figure 2. The key requirements of this system will address the following transformational functionalities:

1. Allow for the integration of renewable energy resources to address global climate change,
2. Allow for active customer participation to enable far better energy conservation,
3. Allow for cyber-secure communications systems to address system safety,
4. Allow for better utilization of existing assets to address long term sustainability,
5. Allow for optimized energy flow to reduce losses and lower the cost of energy,
6. Allow for the integration of electric vehicles to reduce dependence on hydrocarbon fuels,
7. Allow for the management of distributed generation and energy storage to eliminate or defer system expansion to reduce the overall cost of energy,
8. Allow for the integration of communication and control across the energy system to promote interoperability and open systems and to increase safety and operational flexibility.

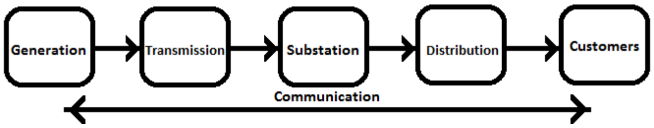

Figure2. The Smart Grid

It should be noted that the Smart Grid, as characterized above, does not replace the existing electric system but rather builds on the available infrastructure to increase the utilization of existing assets and to empower the implementation of the new functionality. For example, centralized sources of generation will still play a major role in the Smart Grid, and large-scale wind and solar generation, wherever cost justified, will become major parts of the generation mix. Availability of a 2-way, cyber-secure, end-to-end communications system will provide consumers with the knowledge Of their energy usage necessary to allow them to locally and/or remotely control their smart appliances and temperature settings. Monitoring and control of the electric system components will provide the utility with the real time status of the system. The use of this real time data, combined with integrated system modeling and powerful new diagnostic tools and techniques, will provide the detection of incipient failures in order to drive preventive maintenance and dynamic work management systems. Automatic reconfiguration of the system, powered by sophisticated, adaptive and autonomous optimization controllers will maintain the flow of energy without interruption when equipment failures do happen. Distributed generation and storage resources and remotely controlled equipment will also play an important role in the management of the Smart Grid energy system not only to address contingency needs but also to optimize power flow, eliminate load pockets, and minimize system losses. It should be noted that building the Smart Grid, as envisioned here, will be very costly and will require a sustained implementation process that evolves over decades.

4.DEFINITION OF THE SMART GRID

The Smart Grid described in this Special Issue is not “pie-in-the-sky” but a true global transformation for which hundreds of billions of dollar-equivalents will be spent within the next decade on real technologies that will provide intelligent management of the electric grid over the coming decades. However, some aspects of the Smart Grid system described herein may turn out not to be cost effective, and they then must wait until cheaper technologies are developed or societal benefits justify the expenditures. That is, the ultimate Smart Grid is a vision, keeping in mind that it requires cost justification at every step before implementation, then testing and verification before extensive deployment. Considering the above, the Smart Grid is defined as an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across electricity generation, transmission, substations, distribution and consumption to achieve a system that is clean, safe, secure, reliable, resilient, efficient and sustainable. This definition covers the entire spectrum of the energy system from the generation to the end points of consumption of the electricity. The reader will note that many definitions proposed by other users are subsets of this system-of-systems definition; as for example, if defined as smart metering, it addresses the consumption and to some extent the distribution part of this definition but not the full spectrum of integration required to implement the Smart Grid. Achieving a smart grid will be a gradual and evolutionary process that will take many decades to be fully realized. To qualify as a Smart Grid, it is neither necessary nor feasible to incorporate all features at one time, but rather incorporation of each new feature can be carried out independently. Each will require cost justification and reasonable pay back on investments. However, interoperability of open systems will allow each addition to “Plug and-Play” into the Smart Grid once the technologies have been validated. Assuming fully realized, the Smart Grid will have the following characteristics that are not available in the conventional electric energy system:

- Secure communications (two-way) covering the system from end-to-end,
- All main components are sensed and variances detected: cables, joints, terminations, transformers, consumer usage, power quality, etc. will be monitored in real time.

The above characteristics will provide massive amounts of incoming data that must be converted into situational awareness of the state of the grid. Controller technologies will then have to automate data and energy management so that information is streamlined, problems are diagnosed instantly, corrective actions are identified and executed dynamically in the field, and feedback loops provide metrics that verify that the work done is producing the desired effects. Such Smart Grid controllers will have the following characteristics

- Self healing: automatic repair or removal of potentially faulty equipment from service
- before it fails, and reconfiguration of the system to reroute supplies of energy to sustain power to all customers,
- Flexible: the rapid and safe interconnection of distributed generation and energy storage at any point on the system at any time,
- Predictive: use of machine and reinforcement learning, weather impact projections, and stochastic analysis to provide predictions of the next most likely events so that appropriate actions are taken to reconfigure the system before next worst events can happen,
- Interactive: appropriate information is provided transparently regarding the status of the system not only to the operators but also to the customers to allow all key participants in the energy system to play an active role in optimal management of contingencies.
- Secure: considering the two-way communication capability of the Smart Grid covering the end-to-end system, the need for physical- as well as cyber-security of all critical assets is essential.
- Management, diagnostic analysis, and work management are required. The Smart Grid must operate as an integrated machine: a system-of systems.

5.ADAPTIVE STOCHASTIC CONTROL

A key to the implementation of the Smart Grid is to create the intelligent management of the margin between the ever-expanding demands for electricity and its efficient, safe, secure, and sustainable supply at all points along the distribution path. Electricity is no longer entering the grid exclusively at massive power plants on the transmission beginnings of the grid, but it will also be generated from distributed resources at customer sites throughout the distribution grid, and even from energy storage at consumer sites and substations. As indicated in Figure 3, intelligent controllers must receive, digest, and interpret all manner of new data coming from SCADA sources and send commands to manage contingencies, optimize power flows, initiate preventive maintenance, control switching and load, minimize capital investment, deal with erratic solar and wind generation, and optimize distributed storage, all the while dealing with potential and real equipment failures as well as weather and price variations.

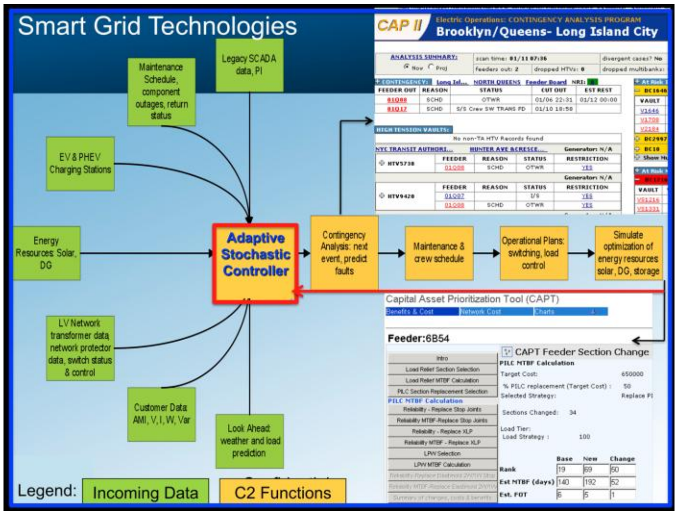

Figure3. The Smart Grid must optimally interpret incoming data from many new sources (green) with new controls such as Contingency Analysis Programs (CAP in the upper right) and Capital Asset Prioritization Tools (CAPT in lower right).

This Smart Grid data and energy management system must be, by definition, adaptive and stochastic, meaning that it is prepared to respond to varying weather conditions, crew status, and equipment performance changes while optimizing supply to meet demand within economic constraints that simultaneously minimize costs for consumers, regulators and industry stockholders. Some utilities now use complex, computational command and control systems similar to those used in petrochemical and nuclear plant management, such as decision support and portfolio management tools, activity based accounting, and preventive maintenance programs. However, the computational systems utilized in these controller calculations are generally policy-and-rules-based decision systems. Risk and variance are considered using linear programming algorithms. These systems are very good at identifying the "next worst" condition that can happen to the electric grid at any given time, but not so good at determining actions to prevent the "next most likely" condition to occur on the electric grid. Controlling the new complexities of the Smart Grid is a multi-stage, time-variable, stochastic optimization problem to the Operation Research engineer and operator. The Adaptive Stochastic Controller (ASC) for the Smart Grid requires the import of Approximate Dynamic Programming (ADP) and Mixed-Integer, Nonlinear Programming solvers that are more familiar to the petrochemical and transportation industries. ADP Adaptive Stochastic Control optimizes by solving the Hamilton-Jacobi-Bellman equation using ADP interacting with the electric system model used by engineering to plan improvements in the grid today.

6. Energy Storage

A critical addition to the Smart Grid will be from the addition of significant energy storage capability. Intermittent power sources like PV, Solar Thermal, and Wind require someplace to store the electricity to fill needs during cloudy and/or windless times. The Electricity Storage Organization tracks the cost of both large and small scale energy storage systems, from Lithium-Ion, Nickel-Cadmium and Lead-Acid batteries, through fly wheels and super capacitors, to various large scale battery storage devices, and finally to large scale cavern storage of compressed air and hydroelectric that involves pumping water back upstream during nights. These technologies are all technologically viable, if affordable: a barrier that has not yet been passed. Until it is, large-scale deployment of alternative energy sources will be limited. Other electricity storage devices that involve melting salt, heating vegetable oils, freezing ice for HVAC chiller operations, and the use of fuel cells have attained wider, though still limited, deployment.

7. WSN-BASED SMART GRID APPLICATIONS

Generally, WSN-based smart grid applications are divided into three groups: consumer side, transmission and distribution (T&D) side, and generation side WSN-based smart grid applications.

- Consumer Side WSN-Based Smart Grid Applications. Consumer side WSN-based smart grid applications have a direct relationship with different types of customers. Consumer side applications include advanced metering infrastructure, residential energy management, automated panels management, building automation, demand-side load management, process control monitoring, and equipment management and control monitoring.
- Transmission and Distribution (T&D) Side WSN Based Smart Grid Applications. T&D side covers overhead power lines, underground power lines, and substations, and the applications designed for this side play a key role in smart grid, since these systems are responsible for successful power transmission. Some of the transmission and distribution side WSN based smart grid applications are overhead transmission line monitoring, outage detection, conductor temperature rating systems, underground cable system monitoring, fault diagnostics, overhead and underground fault circuit indicators, cable, conductor and lattice theft, fault detection, and location.
- Generation Side WSN-Based Smart Grid Applications. These applications are generally based on monitoring task. Some of them are real-time generation monitoring, remote monitoring of wind farms, remote monitoring of solar farms, power quality monitoring, and distributed generation.

Communication and network requirements of smart grid applications play an important role in implementation of WSN technologies for energy distribution infrastructures.

8. Stationary and Mobile Energy Storage Systems

According to a recent U.S. Department of Energy (DOE) report, a future smart grid should accommodate all generation and storage options. As opposed to conventional low-speed controllers, smart storage options augmented by voltage source inverters can effectively address the intermittency and power fluctuation of renewable energy sources, load leveling, shifting power consumption away from peak hours, improving stability margins, fast dynamic active and reactive power support, and power quality improvement. Given the indispensable role of intelligent storage for the stable, secure, and reliable operation of smart grids, government incentives should accelerate the development of storage technologies to reach 150 GWh of utility-scale storage by 2015. The various storage options can be categorized based on technology and mobility (i.e., stationary storage versus storage provided by electrified transportation). Pumped hydro, compressed air, superconducting magnetic storage units, batteries, super capacitors, and flywheels are among the main stationary storage options envisioned for smart grids. Pumped hydro and compressed air systems can store hundreds of MWh and are cost-effective, large-scale storage options, although they are geographically limited. Currently, there are around 40 pumped hydro facilities in the United States. Pacific Gas and Electric is currently studying the feasibility of building a 400–1,200-MW pumped hydro energy storage system on the Mokelumen River in eastern California. Total compressed air storage capacity will grow to around 1.6 GWh worldwide by 2015. Magnetic storage options, e.g., superconducting magnetic energy storage (SMES) systems, are fast-acting and suitable for load leveling, voltage and frequency stability, and improving power quality. Currently, total U.S. installed capacity is around 50 MW. Micro SMES systems with a capacity of less than 10 MW and low-temperature, superconducting materials are under investigation in Europe. Mechanical storage systems, e.g., flywheels, are used for power quality applications, stability improvement, and load shifting. Low-speed flywheels (those running at less than 10,000 rev/min) are commercially available in uninterruptible power supplies (UPS) applications with capacities up to several megawatts. Recently, Beacon Power designed a flywheel frequency regulation plant with a power range of 40 MW and a response time of less than 4 s.

Electrochemical energy storage options have been widely adopted due to their desirable characteristics, such as rapid responses, cycling capability, and relatively low cost. Lithium-ion (Li-ion) batteries are the fastest-growing battery technology in utility-scale applications and will make up more than a quarter of the US$4.1 billion stationary energy storage market by 2018. Sodium-sulfur (NaS) batteries are another viable large-scale storage option, given their high energy density, high efficiency of charge and discharge, long cycle life, and low material cost. Their high operating temperature (300–350 °C) and the highly corrosive nature of their sodium polysulfides make them more suitable for stationary applications. Recent advancements of the technology include solid sodium metals linked to a sulphur compound by a paper-thin ceramic membrane. Such batteries can operate at a lower temperature range (less than 90 °C) and store up to 40 MWh. It is expected that NaS will become the major energy storage technology for smart grid development. Japan has installed more than 200 MW of NaS storage. The largest utility-scale NaS battery in the United States (4 MW), nicknamed “big old battery,” is installed in Presidio, Texas.

Mobile energy storage systems, such as plug-in hybrid electric vehicles (PHEVs), are viable storage options for future smart grids. The overall energy capacity of electric vehicles is expected to reach around 450 GWh by 2020. They can provide ancillary service for load shifting and small-scale reliability enhancement. PHEVs are charged taking into consideration the driving pattern and history

of the vehicle, the required usage time, and the forecast grid demand and are discharged at “idle” times. Using integrated communication infrastructure, smart grid controllers collect information such as load demands, grid voltages and frequencies, and real-time electricity prices to control the charging and discharging process. During a typical trip, a main smart grid energy management center

is updated every couple of minutes with the charge state of vehicle’s energy storage unit and its location via a wireless communication network. An onboard system also manages the energy split between the internal combustion engine (or fuel cell) and the energy storage unit by predicting driving distance. This system shares the information with the main energy management center through wireless communication and is updated with the instantaneous and future load demand. After arriving at the destination, based on power demand and smart grid regulation strategies, the storage unit is charged.

9.CHALLENGES TO ACHIEVING A COMPREHENSIVE SMART GRID

A primary objective of the Smart Grid is to improve our capacity to use more, but cheaper, electricity to power the improvements in the standard-of-living of all people on Planet Earth. However, the transition must be cost effective, or we will never get there from here. The tracking of key performance metrics that continuously and automatically score improvements generated by the Smart Grid will be required if the effort is sustainable over the 20 to 30 years that will be required for a full conversion to a comprehensive Smart Grid in any country. Documenting these improvements requires the establishment of an initial baseline for all major components of the existing grid, and then continuous measurement of the impact of new construction and implementation against that baseline. A benefit from this documentation will be that Adaptive Stochastic Controllers of the Smart Grid will have been validated to redirect load around congestion, manage peak demand, weather and equipment problems that will eliminate the need for expensive new power plants and substations. Internationally, computers operating these Adaptive Stochastic Controllers managing every level of the new Smart Grid could eventually save the need to build Terra-watts of new generation worldwide. Challenges to the future success of the smart grid come from many fronts, such as consumer buy-in: consumers have to see real savings and efficiency improvements; better regulation: governmental control must stay up to date technologically and in touch with consumers; cost justification; Smart Grid components must be individually as well as Systemically cost effective; education: utilities, service companies and universities must produce Educated consumers as well as a new generation of electrical engineer savvy in computer sciences and systems engineering; and new inventions and technologies must be easily adopted and adapted into the Smart Grid since it will evolve over the next 20 to 30 years.

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